Brit. Heart J., 1967, 29, 446.

Phonocardiogram of the Ball-and-Cage Aortic Valve Prosthesis

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The ball-and-cage aortic prosthesis consists of a silastic ball, which has a specific gravity of 1·1499 (S.G. of blood = 1·050), enclosed within a metal cage (Starr and Edwards, 1961). The sounds produced by the ball during its movement about the cage are very characteristic and easily recognized, because they are of high frequency, short duration, and great amplitude. We have studied the phonocardiogram in patients whose aortic valves were replaced by ball-and-cage prostheses, in order to elucidate the mechanisms of these sounds, and to obtain information from them about the phases of the cardiac cycle.

Subjects and Methods

The subjects of this study were 40 patients whose aortic valves had been replaced, 34 with a Starr-Edwards prosthesis and 6 with a Magovern prosthesis. Every patient had at least two phonocardiograms: one before and one after operation. Some had several post-operative phonocardiograms as part of their clinical assessment and whenever their clinical or auscultatory findings changed. The recordings were made by a piezo-electric crystal microphone on a photographic recorder (New Electronic Products, Ltd.). Recordings were made using the high, medium, and low frequency bands. The electrocardiogram was used as a reference trace, and all recordings were made at a paper speed of 80 mm. per sec.

The phonocardiograms were analysed with the aid of a pair of callipers and a hand lens and measurements were made to the nearest 5 msec.

The following measurements were made. (1) Onset of QRS to first heart sound (electrical-mechanical interval). (2) First heart sound to prosthetic valve opening sound. (3) Prosthetic valve opening sound to closure sound. (4) Onset of QRS to closure sound.

These measurements were corrected for heart rate by dividing them by the square root of the R-R interval (Bazett, 1920).

In 15 patients, the phonocardiograms were recorded simultaneously with central aortic and pulmonary artery pressures. These were obtained through nylon tubing inserted percutaneously (Seldinger, 1953) by means of strain gauges (Statham G 23/D.B.), and the whole system had a resonant frequency of 34 c.p.s., with a uniform response up to 12 c.p.s. The delay in transmission of pressures was determined by a simple experiment (Raftery, 1965) and found to be 10 msec. This figure was subtracted from all pressure wave timings.

The behaviour of the valve in a pulse duplicator was studied by means of a hydraulic system consisting of a Starr-Edwards aortic valve mounted in Perspex tubing of uniform diameter. A pulse duplicator (McMillan, 1955) was used to produce intermittent flow across the valve, simulating the heart beat. The movement of the ball was recorded on cine-film at 100 frames a second. During the film exposure, the rate of pulsation, the simulated ventricular pressure, and the peripheral resistance were varied, and the effects of these manœuvres on the movement of the ball were observed.

Results

Systolic Sounds. The most striking feature of the phonocardiogram was the presence of a variable number of sounds associated with the beginning of the ejection period. In every case in this series there was at least one sound of very high amplitude that followed the first heart sound (Fig. 1). This sound, which will be termed the valve opening sound, was of short duration, high frequency, and great amplitude. The first rapid rise of the aortic root pressure pulse always preceded the valve opening sound by 0·02 sec. In many cases a much smaller series of two or three vibrations preceded this main sound, and the timing of these vibrations was found to be simultaneous with the onset of the

Received August 18, 1966.

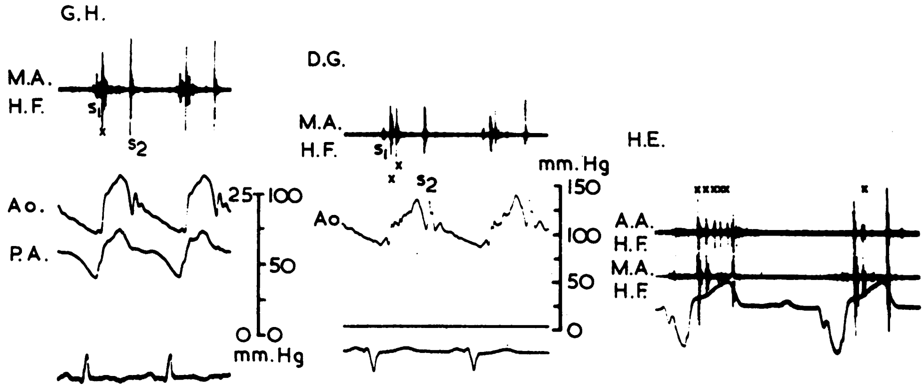

FIG. 1.—Recordings from three patients with Starr-Edwards valves. In the first patient (G.H.) there is a single valve opening sound (x) following the first heart sound and the pressure rise in the aortic root, and a single second heart sound. In the second (D.G.) there are two opening sounds (xx) and in the third there are multiple sounds. Note that the artificial sounds are of high frequency and great magnitude.

S_1=first heart sound; x=valve opening sounds; S_2=second heart sound; MA HF=mitral area: high frequency; AA HF=aortic area: high frequency; Ao=aortic pressure; and PA=pulmonary artery pressure.

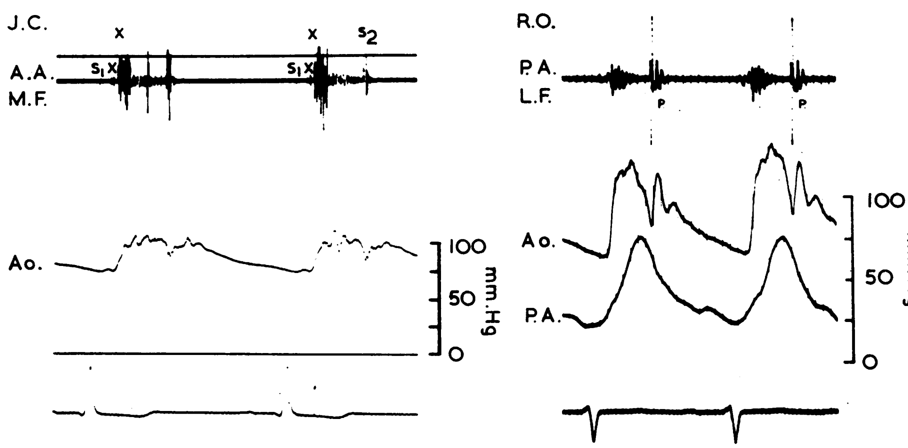

FIG. 2.—J.C.—to illustrate the small group of vibrations (x) which coincides with the pressure rise in the aortic root and precedes the valve opening sound. R.O.—to illustrate the pulmonary component of the second heart sound (P_2) which follows the prosthetic closure sound. Note that P_2 is a low-frequency event. AA MF=aortic area: medium frequency; PA LF=pulmonary area: low frequency.

first rapid pressure rise in the central aortic pressure pulse (Fig. 2).

A variable number of similar sounds was recorded in early systole after the valve opening sound. There was no consistent temporal relation between these and the valve opening sound, and their timing varied in the same patient from beat to beat (Fig. 1).

Second Sound. The prosthetic closure sound consisted of few high frequency vibrations of very high amplitude (Fig. 1), whose duration was short (0·01 to 0·02 sec.). The pulmonary component of the second sound could easily be recorded and was observed to be a low frequency event (Fig. 2).

Murmurs. Two types of aortic systolic murmur were recognizable in these patients: a diminuendo murmur that started immediately after the valve opening sound and lasted about two-thirds of the ejection period, and a diamond-shaped murmur, with an early peak following the opening sound and again occupying only the first two-thirds of ejection (Fig. 3).

Early diastolic murmurs were heard in 4 patients

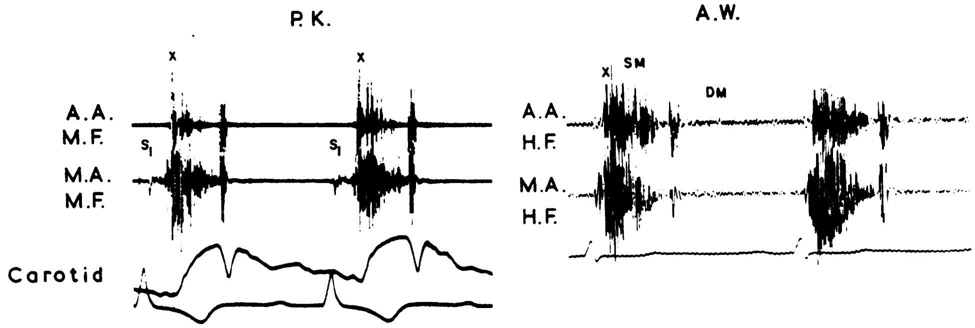

FIG. 3.—Illustrates the murmurs heard after aortic valve replacement. In P.K. the murmur is crescendo-decrescendo and begins after the valve opening sound (x). In A.W. the murmur is maximal about the valve opening sound (x). A long diastolic murmur was recorded also in A.W.

but could be recorded in only 1. In this patient the murmur was seen as high frequency vibrations throughout diastole (Fig. 3).

Phases of Cardiac Cycle. The measured intervals allowed us to estimate the duration of the electrical-mechanical interval, the isometric contraction time, and the ejection time. The values of these intervals are shown in the Table.

Precise measurements of the isometric contraction time and ejection time were obtained in those patients in whom a central aortic pressure was

TABLE

PHONOCARDIOGRAPHIC INTERVALS (SEC.) IN PATIENTS AFTER AORTIC VALVE REPLACEMENT

Patient	R–R	E–M	Corrected E–M	ICT	Corrected ICT	ET	Corrected ET	$Q–S_2$	Corrected $Q–S_2$
H.A.	0·84	0·05	0·05	0·10	0·14	0·25	0·27	0·35	0·42
J.A.	0·67	0·10	0·12	0·09	0·19	0·19	0·23	0·37	0·46
S.A.	0·70	0·06	0·07	0·10	0·14	0·18	0·21	0·31	0·37
I.A.	0·68	0·05	0·06	0·10	0·15	0·18	0·22	0·33	0·39
G.B.	0·71	—	—	—	—	0·21	0·32	0·36	0·43
S.B.	0·62	0·08	0·10	0·08	0·16	0·10	0·25	0·35	0·45
J.B.	0·72	0,06	0·07	0'08	0·14	0·21	0·25	0·35	0·41
J.C.	0·55	0·06	0·08	0·12	0·17	0·15	0·10	0·31	0·42
K.D.	0·54	—	—	0·12	0·16	0·17	0·23	0·35	0·48
M.E.	0·90	—	—	—	—	0·17	0·18	—	—
T.F.	0·67	0·09	0·12	0·11	0·20	0·20	0·25	0·40	0·48
K.G.	0·48	0·08	0·12	0·08	0·14	0·15	0·21	0·29	0·42
W.G.	0·78	0·07	0·08	0·07	0·13	0·18	0·21	0·31	0·36
K.H.	0·79	0·09	0·10	0·07	0·17	0·21	0·24	0·38	0·43
E.H.	0·78	0·06	0·07	0·08	0·14	0·22	0·25	0·36	0·41
J.H.	0·55	0·05	0·07	0·07	0·12	0·18	0·25	0·30	0·40
D.H.	0·54	—	—	—	—	0·17	0·23	0·35	0·48
F.J.	0·62	0·04	0·05	0·06	0·15	0·18	0·23	0·28	0·35
P.K.	0·73	0·05	0·06	0·11	0·11	0·20	0·24	0·35	0·41
Z.K.	0·76	0·05	0·05	0·06	0·17	0·26	0·30	0·37	0·43
F.L.	0·63	0·08	0·10	0·09	0·16	0·22	0·28	0·39	0·49
R.M.	0·84	0·07	0·07	0·10	0·15	0·18	0·19	0·33	0·36
E.M.	0·78	0·09	0·10	0·06	0·10	0·22	0·25	0·37	0·42
E.M.	0·59	0·06	0·07	0·06	0·10	0·17	0·22	0·27	0·35
P.M.	0·65	0·35	0·06	0·05	0,15	0·21	0·26	0·31	0·39
E.N.	0·87	0·04	0·05	0·12	0·17	0·20	0·21	0·35	0·37
J.O.	0·68	0·06	0·07	0·10	0·15	0·14	0·17	0·31	0·38
P.P.	0·66	0·06	0·07	0·09	0·16	0·19	0·23	0·34	0·42
M.R.	0·63	0·06	0·07	0·12	0·17	0·19	0·24	0·35	0·44
E.R.	0·72	0·10	0·12	0·02	0·17	0·18	0·22	0·36	0·43
I.S.	0·82	0·07	0·08	0·07	0·12	0·18	0·20	0·30	0·34
E.S.	0·55	0·07	0·09	0·08	0·15	0·18	0·24	0·33	0·45
G.S.	0·73	0·67	0·08	0·11	0·18	0·22	0·25	0·38	0·48
F.S.	0·65	—	—	—	—	0·21	0·27	0·40	0·49
E.T.	0·68	0·03	0·04	0·08	0·11	0·25	0·30	0·36	0·44
G.T.	0·40	0·05	0·08	0·05	0·10	0·21	0·33	0·30	0·48
F.T.	0·59	0·05	0·07	0·09	0·14	0·18	0·23	0·32	0·42
W.W.	0·52	—	—	—	—	0·21	0·29	0·40	0·47
A.W.	0·90	0·06	0·06	0·04	0·10	0·28	0·30	0·38	0·40
D.W.	0·62	0·06	0·07	0·10	0·15	0·21	0·27	0·35	0·44
Mean Values	0·68	0·06	0·08	0·09	0·14	0·20	0·24	0·34	0·42

R–R = cycle length. E–M = electrical-mechanical interval (Q—first heart sound). ICT = isometric contraction time (first heart sound—valve opening sound). ET = ejection time (valve opening sound—valve closure sound). $Q–S_2$ = beginning of QRS to valve closure sound.

recorded, the first sharp pressure rise being taken to coincide with valve opening. In other cases, valve opening was identified with the group of vibrations that preceded the valve opening sound. Both the electrical-mechanical and isometric contraction times were prolonged when compared with the normal range (Raftery, 1965) and the ejection time was shortened. The QRS to second heart sound interval was also measured and found to average 0·34 sec. This is within the normal range (Shah and Slodki, 1964), because the changes in ejection time and isometric contraction time are in opposite directions and nearly equal.

The relation between these intervals and the cycle length was examined graphically, and no significant relation was observed when the mean values for all the patients were plotted (Fig. 4). On the other hand, when the relation was examined in each individual, it was clear that the electrical-mechanical interval and the isometric contraction interval were inversely related, and the ejection time was directly related to the cycle length (Fig. 4). This suggested that the duration of the phases of the cardiac cycle varied widely between individuals, and closer examination showed that the ejection time, for example, was much longer in the same patient six months after operation than in the immediate post-operative period.

Phonocardiogram During Arrhythmias. Two types of arrhythmia occurred in the patients examined: atrial fibrillation and ventricular extrasystoles. The phonocardiograms recorded during extrasystoles were of great interest. Very early extrasystoles resulted in failure of the valve to open altogether, and though the first sound was recorded (i.e. the atrio-ventricular valves closed) no opening sounds or closure sounds were recorded (Fig. 5). Extrasystoles which occurred later in the cardiac cycle succeeded in opening the valve, but the ejection phase was abbreviated, depending upon the length of the previous diastolic interval. Whenever the extrasystole was followed by a compensatory pause, the post-extrasystolic beat showed a much longer ejection time and much shorter QRS to valve opening sound interval. There was no detectable change in the heart sounds or in the valve opening sounds due to the extrasystoles.

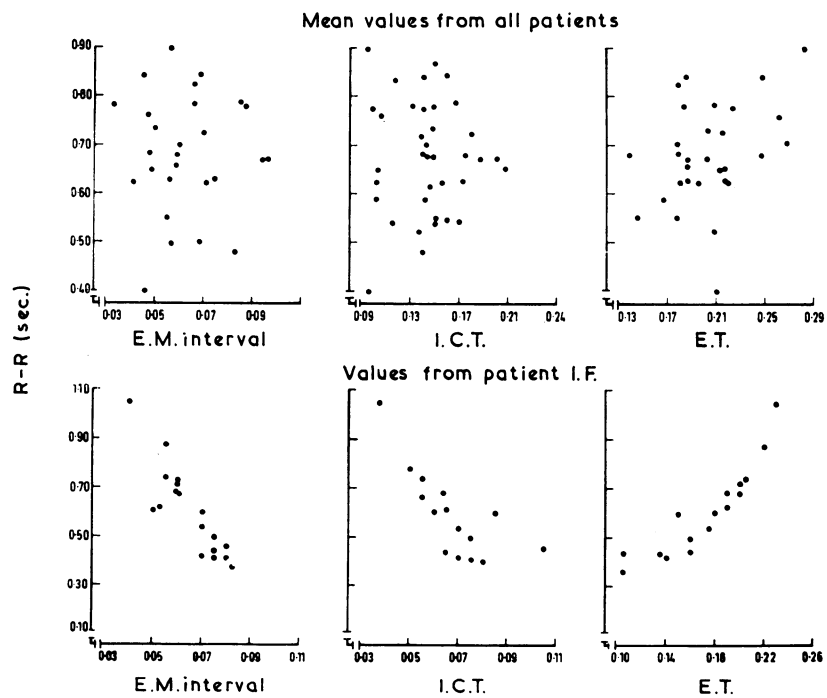

FIG. 4.—Phases of the cardiac cycle plotted against cycle length—mean values (above), values for a single patient (I.F.) with atrial fibrillation (below). The mean values have no clear relation to cycle length, but a linear relation is clearly seen for each phase in the individual patient.

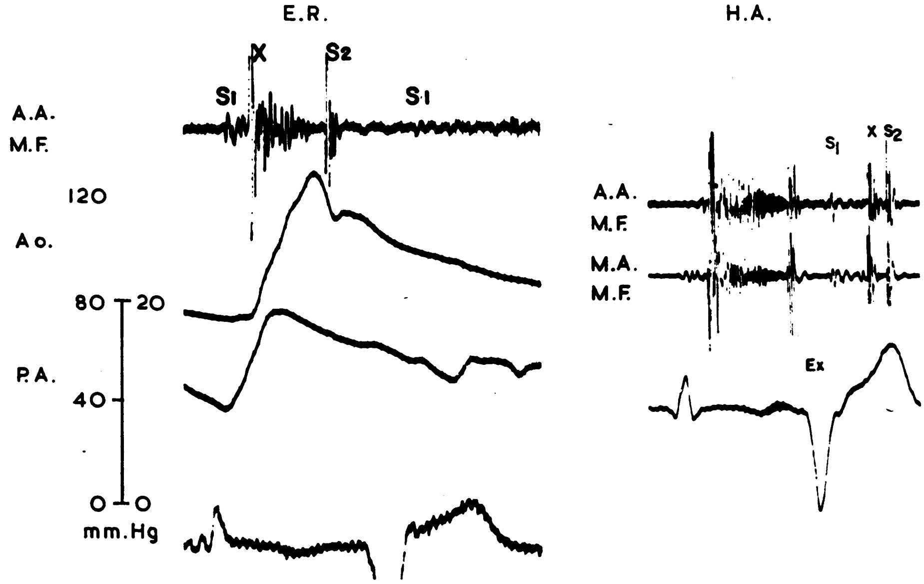

FIG. 5.—To show the effects of extrasystoles. In E.R. the extrasystole produces a first heart sound (S_1) but no opening or closing sounds. In H.A. the opening sound (x) is very late and the ejection phase ($x - S_2$) is greatly reduced. Ex = extrasystole; S_1 = first heart sound; S_2 = second heart sound.

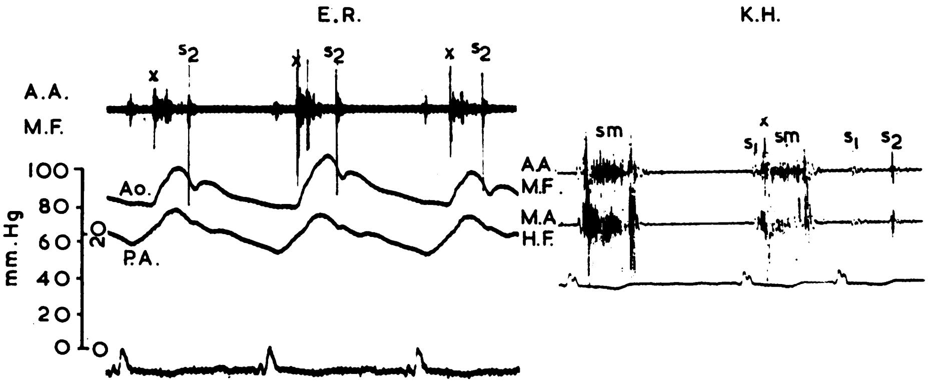

FIG. 6.—E.R.—pulsus alternans identified by long and short ejection periods ($x - S_2$) and alternation of intensity of valve opening sound (x). K.H.—in the third beat there is no valve opening sound (x), though a valve closure sound (S_2) is present. Presumably ventricular ejection was not powerful enough to strike the ball against the cage.

In some instances, the extrasystoles were followed by a normal first heart sound without the usual valve opening sound (Fig. 6). Instead, there was a silent interval, and then the usual second heart sound (i.e. artificial valve closure sound) followed. Pulsus alternans could be identified in two patients by the alternation of long and short ejection intervals (Fig. 6).

Movement of the Valve Ball. The cine-film of the valve in the pulse duplicator showed that when the pulse rate was slow, the ball rebounded from the apex of the cage and struck the sides and apex several times before returning to the base. At fast rates (100/min.) the ball travelled directly to the apex of the cage and stayed there throughout ejection; at rates less than 50/min., it settled out in the midportion of the cage, spinning on its own axis for a considerable portion of the ejection period, before returning to the base.

Discussion

By observing the relation of the sounds generated by the ball-and-cage prosthesis to the pressure events in the aortic root, and observing the behaviour of the ball in an artificial pulse duplicator, it was possible to build up a picture of the way in which the valve behaved during the cardiac cycle. With the rise of left ventricular pressure above that in the aorta in early systole, the silastic ball is dislodged from its ring. This movement produces a very small sound that is not audible and hardly recordable. This is seen in the phonocardiograms with sufficient amplification as a series of small vibrations following the first heart sound (Fig. 2). For the next few milliseconds (mean value 0·02 sec.) the ball travels the length of the cage and then impinges upon the apex. This produces the first major sound which is invariable with every sinus beat. The behaviour of the ball afterwards varies with the physiological conditions. If the stream of blood has a high velocity and ejection lasts for a short period of time, the ball may be forced to remain at the apex for most of the ejection phase, and only one opening sound is recorded in the phonocardiogram. With a longer ejection phase and weaker beats, the ball may be free to leave the apex of the cage and bounce or vibrate in its terminal part, thus producing additional ejection sounds that can easily be seen in the phonocardiogram. Weak beats, e.g. extrasystoles, may dislodge the ball from the ring but may be incapable of moving it to the apex of the cage with sufficient force to produce a sound. Hence the records of absent valve opening sound with a normal closure sound (Fig. 6). Even weaker beats occurring after a very short diastolic phase may not open the valve at all. The force needed to open the valve theoretically depends on the specific gravity of the ball, and as this is nearly the same as blood, very little force should be required to effect an opening. Harken *et al.* (1960) calculated that a minimal pressure gradient of 0·12 mm.Hg would be required to effect opening with an aortic diastolic pressure of 80 mm.Hg. We have observed failure of the valve to open with extrasystoles so frequently that it seems reasonable to suggest that, in practice, the required force is much greater than this.

Consideration of these facts leads to the conclusion that multiple extrasystoles or rapid atrial fibrillation may lead to shortening or abolition of the ejection phase in a significant number of beats per minute and consequently to a marked reduction in the cardiac output. Establishing a slow regular rhythm seems to be important in the immediate post-operative management of these patients.

The ejection phase in these patients was significantly shorter than that of normal persons, accounting for 19 to 55 per cent of the cardiac cycle (mean = 30%). It follows that to produce a cardiac output of 5 litres a minute blood must flow through the valve at a mean rate of 16 litres a minute during the ejection phase. Since flow varies continuously during the ejection phase, the flow rate must be very much greater than this at peak ejection, and even greater values must be reached during exercise. This emphasizes that in designing a prosthetic valve it is vitally important that it should open and close easily, since the duration of the ejection phase in relation to the length of the cardiac cycle is more important than the cardiac output which can be achieved at rest.

The shape and duration of the systolic murmur in valvular aortic stenosis are indicators of the degree of stenosis (Oakley and Hallidie-Smith, 1967), but the arguments which support this observation cannot be applied to the murmur heard after replacement with a ball-and-cage prosthesis. The ball produces considerable turbulence merely by its presence in the aorta, and thus may give rise to a murmur in the absence of obstruction. On the other hand, we have observed that the intensity of the murmur is proportional to the preceding diastolic interval, and since the same relation is seen in valvular aortic stenosis, these murmurs may reflect the gradient which must be established to overcome the inertia of the ball.

The use of the phonocardiogram to detect aortic incompetence has proved disappointing because the early diastolic murmur is very difficult to record. Incompetence can occur either through the ring of the valve or around it, as a result of stitches giving way. In three of the patients in this series, incompetence was found to have occurred around the valve ring and the artificial valve closure sound was similar to that in the patients with no incompetence. In one patient the incompetence was due to fracture of the ball into several large pieces which did not completely seal off the base of the valve, but the opening sound and closure sound on the phonocardiogram were quite normal, and gave no clue to the mechanism of incompetence.

The direct relation between ejection time and heart rate was first pointed out by Wiggers (1949), but the relation between all the phases of the cardiac cycle and heart rate were not clear until recently, when Wallace *et al.* (1963) made careful observations in the dog. In our patients, when the mean values for these phases were plotted against mean cycle length for each patient, no consistent relation emerged, and yet when the individual values were plotted in those patients in whom the cycle length varied (i.e. those with atrial fibrillation), it could be seen that the expected relations were indeed present (Fig. 5). This suggested that the exact relations differed in different patients, presumably as a result of differences in myocardial function. Shah and Slodki (1964) suggested that the QRS to second heart sound interval was a good indicator of the duration of ventricular systole, and gave some indication of ventricular function in normal and hypertensive patients. Our observation that this interval was consistently within the normal range in our patients suggests that it may be misleading in patients after cardiac surgery.

Our observation of an inverse relation between isometric contraction time and cycle length appears to conflict with the experimental observations of Sarnoff and his associates (Wallace *et al.*, 1963) in dogs. In fact this is probably a reflection of the changes in stroke volume with a changing R-R interval, and is further confirmatory evidence for the importance of stroke volume in determining the duration of the phases of the cardiac cycle.

Summary

The sounds and murmurs produced by the ball-and-cage aortic valve prosthesis have been studied and described. A number of opening sounds may occur, and observations on their mechanism of production have been made. Systolic murmurs were common, but diastolic murmurs were very difficult to hear or record, even when incompetence was severe. The phonocardiogram did not safely allow distinction between incompetence around the artificial valve ring and incompetence around the ball. The phases of the cardiac cycle were accurately measured, and isometric contraction was found to be prolonged while the ejection time was shortened. The QRS to second heart sound was within the normal range, and it is suggested that this interval is not a good indicator of myocardial function in patients after cardiac surgery. It is also suggested that a slow heart rate is important for survival in the immediate post-operative period.

Our thanks are due to Professor J. F. Goodwin, Professor H. H. Bentall, and Mr. W. P. Cleland for their kind collaboration in this study. The illustrations were produced by the Photographic Department of the Postgraduate Medical School.

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